ARIZONA DEPARTMENT OF TRANSPORTATION

INTERMODAL TRANSPORTATION DIVISION
JOINT PROJECT ADMINISTRATION
205 South 17th Avenue - Room 293E, Mail Drop 616E
Phoenix, Arizona 85007

JANE D. HULL
Governor

MARY E. PETERS
Director

THOMAS G. SCHMITT
State Engineer

E. JACK HAMMITT
Joint Project
Administrator

12 November 1998

Ms. Lee Anne Peters
Financial Analyst Principal
Office of Research and Contract Analysis
University of Arizona
888 N. Euclid Avenue #412
Tucson, AZ 85721

Re: VISTA Program
Agreement: JPA 98-161
TRACS No. H5176 01X
Amendment No. 1

Dear Ms. Peters:

The ADOT Equipment Services Administrator has requested additional details relating to the terms of the vehicle to be provided to U of A be included in the agreement. We may use this instrument as Amendment No. 1. Therefore, the following terms are incorporated;

The rental for the vehicle is $1.00 per month. The vehicle is to be provided to the University for 1 year. The University will provide all preventive maintenance, repair, fuel and related items. The vehicle will be returned to ADOT in the same condition that it was when provided to the University, less fair wear and tear. All other terms and conditions of the agreement remain the same.

To properly memorialize this amendment, and to insure a meeting of the minds, please indicate your concurrence of this amendment in the space provided below and return one original of this instrument to the undersigned at the above address to the attention of Mail Drop 616E. Questions may be directed to the undersigned at (602) 255-8369 or Mr. Steve Owen at 255-6910.

Sincerely,

E. Jack Hammitt

E. Jack Hammitt, CPM
Joint Project Administrator

Concur for the University of Arizona:
Arizona Board of Regents

By Lee Anne J Peters

Date 11/23/98
(date)

Encl.

AG Contract No.KR98 2119TRN
ADOT ECS File: JPA 98-161
Project No. H5176 01X
Research: VISTA (Research on Vehicles with Intelligent Systems for Transport Automation)

INTERAGENCY AGREEMENT
BETWEEN
THE DEPARTMENT OF TRANSPORTATION
AND
THE UNIVERSITY OF ARIZONA

THIS AGREEMENT is entered into 4 November, 1998, between agencies of the State of Arizona, to wit; the DEPARTMENT OF TRANSPORTATION (the "DOT") and the ARIZONA BOARD OF REGENTS, acting for and on behalf of UNIVERSITY OF ARIZONA, (the "University").

I. RECITALS

1. The DOT is empowered by Arizona Revised Statutes Section 28-401 and 28-334 to enter into this agreement and has by resolution, a copy of which is attached hereto and made a part hereof, resolved to enter into this agreement and has delegated to the undersigned the authority to execute this agreement on behalf of the DOT.

2. The University is empowered by Arizona Revised Statutes Section 15-1626 to enter into this agreement and has delegated to the undersigned authority to execute this agreement on behalf of the University.

3. The Arizona Legislature has allocated state funds in the amount of $100,000.00 to be administered by the DOT to conduct Research on Vehicles with Intelligent Systems for Transport Automation (VISTA) at the University. The mission of the VISTA program will be to perform advanced research in automated highway concepts, particularly with intelligent vehicle guidance and control systems. This agreement is to define the terms of the transfer of funds from the State to the University and the expenditure thereof.

THEREFORE, in consideration of the mutual agreements expressed herein, it is agreed as follows:
===

II. SCOPE OF WORK

1. The DOT will:

a. Appoint a Project coordinator to interface with the University relating to the VISTA program research and project development.

b. Provide the University with information and data as may be reasonably available to assist in the VISTA project research and development. Make available to the University, on a $1.00 per month rental basis, a suitable vehicle for testing.

c. Reimburse the University allowable and allocable costs of work performed directly relating to the VISTA program within forty-five (45) days after receipt and approval of monthly invoices, in a total reimbursement amount not to exceed $100,000.00.

2. The University will:

a. Appoint a Project coordinator at the University (U of A) to interface with the DOT relating to the VISTA program research and various project development. If provided a vehicle by the DOT, be responsible for all risk responsibility while the vehicle is under University control, and return the vehicle to the DOT in its original condition, less fair wear and tear.

b. Accomplish the work generally in accordance with Exhibit A, which is attached hereto and made a part hereof, provide the DOT monthly, quarterly and final VISTA project reports and other deliverables; such reports will accompanied by a summary of expenditures. Such reports will be in a format compliant with the DOTs "Guidelines for Preparing Research Reports."

c. No more often than monthly, invoice the DOT in the form of Exhibit B attached hereto.

III. MISCELLANEOUS PROVISIONS

1. Title to all documents, reports and other deliverables prepared by the University in performance of this agreement shall rest jointly with the State and the University.

2. This agreement shall become effective upon signature by the parties hereto, and shall remain in force and effect until completion of said project and reimbursements; provided, however, that this agreement, may be cancelled at any time prior to the commencement of performance under this agreement, upon thirty (30) days written notice to the other party.

3. The parties agree to comply with all applicable state and federal laws, rules, regulations and executive orders governing procurement, equal employment opportunity, immigration, nondiscrimination and affirmative action.

4. This agreement may be cancelled in accordance with Arizona Revised Statutes Section 38-511.

5. The provisions of Arizona Revised Statutes Section 35-214 are applicable to this contract.

6. In the event of any controversy which may arise out of this agreement, the parties hereto agree to abide by required arbitration as is set forth for public works contracts in Arizona Revised Statutes Section 12-1518.

7. All notices or demands upon any party to this agreement relating to the agreement shall be in writing and shall be delivered in person or sent by mail addressed as follows:

Department of Transportation Joint Project Administration 205 S. 17th Avenue - 616E Phoenix, AZ 85007	University of Arizona Research & Contract Analysis 888 N. Euclid Ave. #412 ~~2030 E. Speedway Room 222~~ PO Box 210158 Tucson, AZ 857~~19~~ 21 LTP

8. The parties recognize that performance by the U of A under this Agreement may be dependent upon the appropriation of funds by the Arizona State Legislature. Should the state at any time fail to assign the necessary funds for such performance, the DOT or the U of A may cancel this agreement.

IN WITNESS WHEREOF, the parties have executed this agreement the day and year first above written.

STATE OF ARIZONA

THE ARIZONA BOARD OF REGENTS acting for and on behalf of THE UNIVERSITY OF ARIZONA	**DEPARTMENT OF TRANSPORTATION**
By LeeAnne T. Peters LTP LEEANNE PETERS Financial Analyst Principal Office of Research and Contract Analysis	By Tim Wolf TIM WOLFE Ass't State Engineer

98-161
9sep

JPA 98-161

RESOLUTION

BE IT RESOLVED on this 9th day of September 1998, that I, the undersigned MARY E. PETERS, as Director of the Arizona Department of Transportation, have determined that it is in the best interests of the State of Arizona that the Department of Transportation, acting by and through the Intermodal Transportation Division, to enter into an agreement with the University of Arizona for the purpose of defining responsibilities for conducting research on the intelligent vehicles (VISTA) program.

Therefore, authorization is hereby granted to draft said agreement which, upon completion, shall be submitted to the Assistant State Engineer for approval and execution.

DAVID ALLOCCO, Manager
Engineering Technical Group
for Mary E. Peters, Director

A PROPOSAL

FOR THE DEVELOPMENT OF THE

VISTA Program:
Research on Vehicles with Intelligent Systems for Transport Automation

Submitted by

PITU B. MIRCHANDANI
Systems and Industrial Engineering Department
The University of Arizona

FEIYUE WANG
Systems and Industrial Engineering Department
The University of Arizona

&

C. Y. KUO
Mechanical and Aerospace Engineering Department
Arizona State University

Submitted to

ARIZONA DEPARTMENT OF TRANSPORTATION

August 28, 1998

EXECUTIVE SUMMARY

This proposal seeks support from the Arizona Department of Transportation to establish a research program in Intelligent Vehicles and Automated Highway Systems, referred to as the *VISTA* (Vehicles with Intelligent Systems for Transport Automation) Program. *VISTA*'s mission is to develop an affordable vehicle that can be deployable within the next 5-10 years. By this it is meant that the additional infrastructure required on the corridor should be minimal, the Intelligent Vehicle (IV) and the Automated Highway System (AHS) should be robust and reliable, defined measures of effectiveness (travel time, safety, cost, etc.) should be specified or optimized, and impacts on air quality and energy consumption should be minimal.

VISTA will consider the following "new" concepts for its design of IV-AHS:

1. The use of a hierarchical control structure that requires less frequent, and less spatially dense, communication between the traffic operations center (TOC) and the vehicles, and requires less computational effort for lateral and longitudinal control of the vehicle on the highway. Fuzzy control logic will be used in a two-level hierarchy. By providing both long- and short-range roadway information, path planning (open-loop control) and trajectory control (closed-loop feedback control) can be conducted in a hierarchical and optimized fashion. No current vehicle control system has the feature of path planning which makes it possible for an IV to optimally schedule its speed and position for a longer time window, while the short-range road information provides the needed feedback to follow its lane closely at the times.

2. The use of cheaper sensor technology for establishing vehicle position and implementing feedback control. Long- and short-range sensing strategies are complementary to each other. On one hand, long-range road information can simplify short-range sensing data processing and make its result more robust and accurate against failures and noises. On the other hand, short-range position information can facilitate the process of finding the relative position of the vehicle with respect to the roadway for the next 100-300 meters. Furthermore, the reliability for short-range sensing may be improved since the system is not restricted to single sensing technology. Dead reckoning control algorithms using the long-range markers can safely assist the vehicle to appropriately respond when short-range sensors fail.

It is anticipated that the proposed system will be cost effective, robust and reliable and enable better control and motion.

To conduct the proposed research, the *VISTA* team will lease or buy a used vehicle for demonstration puposes and enhance it with sensor systems and automatic longitudinal and lateral control systems. It will demonstrate IV concepts, in a laboratory setting in Tucson and Tempe and on a highway in Phoenix. The research team will also compare and evaluate available IV technologies and perform preliminary analysis for Phoenix-Tucson Intelligent Lanes.

The research team will actively seek the collaboration, and possible funding, for future research through partnerships with other public agencies (in addition to ADOT and USDOT) and companies that may find *VISTA*'s research and products very beneficial.

The research team will consist of Professors Pitu Mirchandani and Feiyue Wang from the UA, Professor C. Y. Kuo from ASU. In addition, they will be assisted by Dave Bruggeman from BRW Inc. Together they bring to bear the right experience and expertise to make this a successful project.

Most of the algorithmic and system development, including the bench test of software/hardware, will be conducted on the UA campus, where Professor Wang will coordinate the associated efforts of the faculty and students. The demonstration and the field testing will be conducted in the Tempe (at ASU) and in the Phoenix area, coordinated by Professor Kuo. Professor Mirchandani will coordinate the evaluation of system design alternatives for the Phoenix-Tucson corridor and will oversee the overall project performance, including facilitate UA-ASU interactions.

At the present, the research team is proposing a research program, entitled the *VISTA* Program, which will be administered through the *ATLAS* Research Center of Excellence being established at The University of Arizona. When the *VISTA* Program grows, as it is currently anticipated, Board of Regents approval will be sought for making this a multi-university research center.

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VISTA PROGRAM:
VEHICLES WITH INTELLIGENT SYSTEMS FOR TRANSPORT AUTOMATION

1. INTRODUCTION AND OVERVIEW

This proposal seeks support from the Arizona Department of Transportation to establish a research program in Intelligent Vehicles and Automated Highway Systems, which will be referred to as the *VISTA*[1] Program in the sequel. The *VISTA* Program will initially involve two research faculty from the University of Arizona (UA) and one from Arizona State University (ASU). In subsequent years, when the program has additional research finding available, it will encourage and allow participation of other research faculty from UA and ASU, as well as Northern Arizona University (NAU).

For the year 1998-1999, the *VISTA* program will conduct a preliminary analysis of alternatives for an intelligent vehicle corridor between Tucson and Phoenix, develop one or more (up to three) technologies for demonstration of alternatives, propose further design and development of a recommended alternative, and seek partnerships and collaborations for future research and projects. In subsequent years, the *VISTA* program will develop the "*Intelligent Vehicle of Arizona*" - *IVA*- (corresponding to the CMU's "Intelligent Vehicle" and UC Berkeley's "PATH Vehicle"). It should be noted that the fundamental differences between the Research Team's proposed technologies/systems and existing technologies/systems used in current concepts are based on the Team's mission **to develop an affordable vehicle that can be deployable within the next 5-10 years**. Attributes that the research team will look for on the design of the Tucson-Phoenix Intelligent Vehicle corridor and the *IVA* are:

1. the additional infrastructure required on the corridor should be minimal, and affordable,
2. the system should be robust and reliable,
3. defined measures of effectiveness (travel time, safety, cost, etc.) should be specified or optimized, and
4. impacts on air quality and energy consumption should be minimal (in fact, it is anticipated that intelligent vehicles and automated highway systems would increase air quality and decrease energy consumption).

[1] Vehicles with Intelligent Systems for Transport Automation

2. EXPERIENCE AND EXPERTISE OF THE RESEARCH TEAM

Professors **Pitu Mirchandani** and **Feiyue Wang** from the UA, Professor **C. Y. Kuo** from ASU will be the principal investigators on the project. In addition, they will be assisted by **Dave Bruggeman** from BRW Inc. Together they bring to bear experience and expertise in

1. Transportation and traffic systems
2. Systems engineering
3. Software systems
4. Automobile technologies
5. Vehicle dynamics
6. Intelligent control and robotics
7. Machine vision

Dr. Pitu Mirchandani (Sc.D. '75, MIT) is a Professor of Systems & Industrial Engineering and Electrical & Computer Engineering at the University of Arizona. His areas of technical expertise include systems design, logistics, optimization, and real time decision systems. His research interests have focused on the modeling of spatial and temporal interactions for the design and decision-making in spatially distributed systems which include transportation and communication systems. Dr. Mirchandani has also been on the Hughes - Delco - GM team proposing an AHS architecture (1993-1995) and has participated in the first AHS workshop in 1994. He has over 60 publications including two books. He is a member of *IEEE, INFORMS, IIE, ACM, TRB, ITS America* and *ITS-Arizona.*

Dr. Mirchandani has been a principal investigator on several projects in traffic and transportation systems including the current *RHODES-ITMS Project* funded by Arizona Department of Transportation, and the FHWA Projects on The *Development of a Real-Time Traffic Adaptive Signal Control Prototype* and *Open-systems Communication/Control Architecture for Real-Time Traffic Adaptive Signal Control.* These projects have received national recognition and have enabled the University of Arizona to establish a Research Center of Excellence *in Advanced Traffic and Logistics Algorithms and Systems* (*ATLAS*), initially funded by the FHWA. The proposed *VISTA* Program will be administered through this Center.

Dr. Feiyue Wang (Ph.D., '90, Rensselaer) is an Associate Professor of Systems and Industrial Engineering at the University of Arizona. His areas of technical expertise include intelligent control, real-time embedded systems, mechatronics, robotics and automation, computer vision, and operation control and scheduling.

Dr. Wang has been a principal investigator or co-investigator on several projects in intelligent vehicle automation including the Intelligent Robotic Vehicle for Lunar and Martian Resource Assessment funded by NASA and the Automated Excavation Technologies for Wheel Loader currently funded by Caterpillar Inc. He has also received various research contracts on manufacturing, process control, robotics and automation from NSF, DOE, AT&T, and BHP. Dr. Wang has published more than 50 refereed journal articles and book chapters, and more than 100 conference papers and technical reports.

Dr. C. Y. Kuo (Ph.D. '85, UC Berkeley) is an Associate Professor of Mechanical and Aerospace Engineering Department at Arizona State University. His areas of technical expertise include control, system dynamics and computer simulation. He is an active researcher on the topics of real-time, intelligent control of mechanical systems such as robots and vehicles, tactical missile guidance, vibration control, robust and optimal control, system identification and instrumentation. He has published over 35 major journal and conference papers.

Dr. Kuo has received various research contracts on control research from federal agencies and industrial sponsors, including the MAX project funded by Motorola on fuzzy logic control of mechanical systems. Dr. Kuo has been an active participant in various national and international conferences and organizations for control research.

Dave Bruggeman (PE), Vice President BRW Inc., has extensive experience in Traffic Engineering. He has been a major player on several ITS projects, especially Automated Highway Systems (AHS) investigations. He has conducted precursor systems analysis studies in (i) AHS - Roadway Deployment, and (ii) AHS - Daily Operations. He was a principal speaker at the first AHS Workshop (1994) where he presented AHS deployment and operational issues. In fact, very relevant to this project, Dave Bruggeman was the Principal Investigator and main author of the *Concept Study on Intelligent Express Lanes I-10, Phoenix to Tucson* that was recently sponsored by the Arizona Department of Transportation.

3. BACKGROUND

3.1 Programmatic Background

Given the continuously increasing traffic congestion on the national highways, an approach to mitigate the delays and safety problems associated with this congestion is the introduction of Intelligent Vehicles and Automated Highway Systems. Over the last few years, the USDOT has expended significant resources and effort into feasibility studies of AHS and the development of concepts, architecture, and technologies for AHS. Specifically, after USDOT conducted the feasibility studies, the National Automated Highway System Consortium (NAHSC), consisting of public agencies (including FHWA, Caltrans, etc.) and private companies (such as GM, Motorola, Hughes, etc.) was formed to refine promising concepts and move toward deployment.

In August 1997, the NAHSC presented its first public demonstration of AHS in San Diego, CA. This proof of technical feasibility demonstration was requested by the US Congress in the 1991 ISTEA legislation, which read in part: "*The Secretary of Transportation shall develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highway systems can be developed ... The goal of this program is to have the first fully automated roadway or an automated test track in operation by 1997.*"

It has been realized that a one-step deployment of AHS is both impractical and extremely expensive and thus the emphasis has shifted to the development of technologies that can be incrementally introduced and tested which would be beneficial now but fully beneficial when a complete AHS is employed where platoons of vehicles will travel from point to point at very high speeds with little or no interactions with the drivers (unless they are getting on or off the AHS). An example of such a technology is *Adaptive Cruise Control* (ACC). This allows a vehicle to follow another vehicle with a very short headway where the following vehicle will automatically accelerate or slow down when the leading vehicle accelerates or slows down. In the USA, ACC is being developed as an option in high-end cars; it is already available as an option in some cars in Japan.

Another incremental deployment technology is the Intelligent Vehicle. The idea here is to put as much intelligence in the car as possible so that it is *semi-autonomous*, requiring very little instruction or interaction from the driver of the vehicle. At a minimum, an intelligent vehicle will need ACC, a mechanism to sense its position, and a mechanism that provides feedback for control after the position has been validated. The CMU Intelligent Vehicle referenced above uses machine vision to sense its position with respect to marked lines on the pavement, whereas the PATH vehicle uses feedback from magnetic lane markers to sense the vehicle's position with respect to the AHS lane being used.

The most costly aspect in the deployment of AHS is its infrastructure. Protected lanes need to be constructed, mechanisms for entering and exiting the lanes (at a few points) need to be implemented, communication/electronic equipment must be installed for continuous monitoring of the vehicles in the lanes and, if required, for mechanizing the strategies for coordinating the control of the vehicles.

Fortunately, there is a "window of opportunity" where planned infrastructure expenditures may be used, with some additional funding from USDOT , ADOT and private entities, to construct "Intelligent Lanes" between Phoenix and Tucson so that AHS may be deployed. Considering the traffic forecasts into year 2020, ADOT has identified the need for a third lane between the two cities by year 2005 and a forth lane by the year 2020 [Bruggeman, 1997]. Thus, whether or not AHS is deployed, it is extremely likely that ADOT will have planned expenditures to build one or two more additional lanes between Phoenix and Tucson. When construction of these additional lanes is beginning, if it has been shown (by the *VISTA* Program and other research and planning efforts) that deployment of AHS is both feasible and beneficial, then it is possible that lane barriers and communication/electronics infrastructure can be included in this construction with minimal additional cost. In fact, the recent study by BRW [Bruggeman, 1997] proposes a six-phase three-track approach that addresses both the need to increase capacity of the Phoenix-Tucson corridor and the development and deployment of AHS if deemed necessary. Track 1 is aimed at providing incentives for drivers to use equipment that will enable intelligent vehicle operations (e.g., ACC); Track 2 involves the installation of communication/electronics infrastructure to communicate with the intelligent vehicles (e.g., monitoring of individual cars in the intelligent lanes); Track 3 is to integrate the intelligent vehicle with the intelligent infrastructure and to operationalize the AHS, at least to the level needed for operational testing. BRW proposes a phased approach to the implementation, with full operational testing of developed intelligent vehicles, technologies and products taking place by year 2009, and having exclusive lanes for intelligent vehicles by year 2020 (in anticipation that a large number of them will be operating by then). The reader is referred to the BRW study for a proposed implementation schedule and plan.

Although BRW discusses various options for the technologies that may be used for the Phoenix-Tucson corridor, it does not recommend any specific technology that will be most suitable for this purpose. In fact, the three major issues in the choice of the technology are that (a) "intelligence" in the vehicle must be affordable by a large segment of the Arizona population, (b) the infrastructure should be initially usable by conventional vehicles (while the intelligent vehicles and the infrastructure equipment are being developed) and (c) the additional agency (USDOT/ADOT) cost for equipping the infrastructure is not prohibitive to make the AHS non-beneficial. That is why the research team will investigate, in addition to those currently developed, new technologies and concepts that address the above issues. In particular, it will include the consideration of the following "new" concepts as far as AHS is concerned:

1. The use of a hierarchical control structure that requires less frequent, and less spatially dense, communication between the traffic operations center (TOC) and the vehicles, and requires less computational effort for lateral and longitudinal control of the vehicle on the highway; and

2. The use of cheaper sensor technology for establishing vehicle position and implementing feedback control.

3.2 Technical Background

Improved safety and traffic flow, without constructing new highway facilities, are the two most important motivational factors behind the concepts and technologies for intelligent vehicles (IV) automated highway systems (AHS). These factors, however, neither directly compete nor are directly complementary. Partly due to different emphases of these two factors, different approaches, architectures and technologies have been developed by various groups for IV-AHS over the past decade.

Even though the exact configuration of future IV-AHS has not been decided, it is generally agreed that AHS will involve intelligent vehicles equipped with advanced sensors and computer-based control systems. Also, the infrastructure will be actively involved in managing and controlling the traffic flow by using sensor and control technologies. These new hardware/software designs would improve safety and allow vehicles to move at higher speeds with smaller headways. This, in turn , would considerably increase the capacity and efficiency of a highway system.

Currently, the two most significant system concepts are the vision-based *free agent architecture*, led by Carnegie Mellon University [Bayouth and Thorpe 1996], and the magnetic-nail-based *platoon architecture*, led by the University of California, Berkeley, PATH program [Zhang 1997].

Free Agent Approach: The free agent approach eliminates the need for extensive highway rebuilding and allows a gradual, evolutionary shift to fully automated highways. It also eliminates the risk of widespread system failures and improves integration with urban surface streets.

Platooning Approach: Improved traffic throughput is the major advantage of the platooning scheme, in which large groups of intelligent vehicles travel together with small intra-vehicle spacing (a meter or two) and inter-platoon headway of a second or two. For example, for platoons of 20 vehicles in average, this method can quadruple highway capacity [Varaiya 1993], thereby reducing the need for building more/bigger highway facilities.

There is no right answer to which approach is better, the platoons or the free agents. Each approach has its advantages and disadvantages. Eventually, this research team believes that the final deployed IV-AHS will be the combination of both methods, that is, an IV would be capable of both participating in a platoon as a leader or follower, and driving autonomously as a free agent. This combination will ensure the IV-AHS goals of both improved safety and efficient traffic flow.

3.3 Current Technologies

A focus of this project will be on control of intelligent vehicle operations. Broadly speaking, vehicle control problems can be divided into two classes: longitudinal control for maintaining safe distance from the preceding vehicle and lateral control for keeping the vehicle in the center of the lane and changing lanes as needed.

Longitudinal Control: The longitudinal controllers use sensors to obtain relative velocity and distance from the car ahead as well as self-state sensors that provide measurements of its own velocity, acceleration, engine state, etc. Both the accelerator and the brake must be automatically controlled to achieve the desired result.

Currently, the most commonly used sensing methods for longitudinal control are radar/laser-based technologies. Various control algorithms for headway maintenance have been developed and tested. Adaptive cruise control (ACC), which can sense a slower moving vehicle ahead and slow itself to avoid a collision, has become commercially available. Intelligent cruise control (ICC) and cooperative adaptive cruise control (CACC), which add communications to ACC, should also be commercially available in near future. CACC would enable vehicle-to-vehicle communication as well as vehicle-to-infrastructure communication. This will allow shorter following distances between equipped vehicles since braking would be detected faster, thus lead to an increase in highway capacity and safety, and a reduction in fuel use and emissions since it allows a vehicle to automatically adapt to speed restrictions for curves.

Lateral Control: Lateral control is more difficult than the longitudinal control. Lateral controllers use sensors to identify lanes, curves, obstacles, and nearby vehicles on adjacent lanes - for following roads, changing lanes and avoiding obstacles. More sophisticated and expensive sensing technologies are required for these purposes. Lateral control is essential for safety improvement and for a smoothing of traffic flow on highways of multiple lanes. When only single-lane operation is involved, lateral control does not contribute to the capacity benefit.

Most commonly used sensing technologies for lateral control are vision-based methods. One of the major advantages of vision-based road reference systems is that they require few infrastructure changes. However, a considerable computing power is required to process the data and it may not be effective under certain weather conditions such as snow, heavy rain, fog or at night. The vision system used in all CMU intelligent vehicles in the *1997 Demonstration of Automated Driving* organized by NAHSC was RALPH [Pomerleau and Jochem, 1996]. This system uses a forward-looking video camera mounted behind the rear view mirror of the cars (or the inside of the windshield for buses) to image the road. The image is transformed to produce an overhead view of the road. The overhead view is then processed to find the road curvature. This effectively finds the curve that most closely follows all visible road features. RALPH provides output on a RS-232 line which includes among other things, the vehicles current lateral position relative to the lane center, yaw relative to the lane centerline, and road curvature.

Several other alternatives to vision system have also been developed [Thorpe and Jochem, 1998]. The permanent **magnetic marker system** is the most reliable one but also the most expensive especially when road curvature information is to be encoded as marker patterns to provide the lateral controller preview information. Westrack, the Nevada Automotive Testing Center, has implemented automated truck steering based on following a **buried cable**. The lateral position is sensed by putting an audio-frequency signal on the cable and picking the signal up with coils mounted under the front bumper of the tracks. Several systems in Europe utilize **mechanical guideways** such as O-Bahn (reference), which uses concrete rails on both sides of the road. The O-Bahn approach can provide an effective service but is probably not easily applicable to mass use. **The radar-based frequency selective strip** (FSS) technology developed by the Ohio State University is another interesting alternative [Ozguner, 1977]. FSS is lane marking tape with an aluminum foil layer in the middle. The foil has slots punched in it, spaced to provide a strong return from an automotive radar at a particular shallow angle. It is also possible to use **laser sensors** for lateral control. One advantage of radar/laser technologies is that the same sensor can have dual use: (i) to see other vehicles on the roadway and (ii) also its position in the lane.

These different approaches to IV-AHS are appropriate. First, it makes more sense for different research groups to explore alternatives rather than to build duplicate technologies, especially at this early stage of IV-AHS development. But more fundamentally, different technologies emphasize different objectives, have different geographic/environmental considerations, and have different advantages/disadvantages.

4. PROPOSED TECHNICAL APPROACH

The major goals of the *VISTA* Program are (1) to evaluate and test different technologies for IV-AHS, (2) to demonstrate one or more of these technologies towards the development of the "*Intelligent Vehicle of Arizona*" (*IVA*) and (3) to study and develop appropriate technologies and system architecture that are cost effective and deployable for an intelligent vehicle corridor between Tucson and Phoenix.

A phased approach will be implemented to accomplish *VISTA*'s goal. In the first phase, one or two intelligent vehicle prototypes will be developed to test and evaluate different architectures, control strategies, and sensing methods. A proof of technical feasibility will be demonstrated at ADOT's test roadway in north Phoenix. This phase will be completed in the first year of the Program. Full operational tests of technologies and systems that may be commercially viable will be carried out in future phases.

4.1 Demonstration Vehicle

VISTA's demonstration vehicle will be equipped with advanced sensors and computer-based control systems. In addition, to execute the commands for longitudinal control, it will have actuators for vehicle acceleration and deceleration. For lateral control, rotation of the steering wheel will be handled by the on-board control computer.

Three major hardware modifications need to be made on a commercial vehicle before it can become a demonstration test vehicle for the *VISTA* Program. First, its cruise control system has to be operated by an on-board control computer which provides the desired speed. This will involve some rewiring and should be a straight-forward task. Second, the steering mechanism of the vehicle needs to be modified so that the control system can direct the vehicle's motion. This can be achieved by coupling a stepping servo motor to the steering mechanism. Third, and possibly the most challenging, is the modification for controlling the braking action. This can be achieved by installing a translational actuator which operates on the vehicle's hydraulic power braking system much like a human operator's foot. Since there have been earlier examples of similar vehicle modifications, such as those done by the PATH Program and CMU, no major technical difficulties are expected for the *VISTA* Program. Visits to the PATH Project and CMU will be arranged at the beginning of the project.

4.2 Fuzzy Control Technologies

The performance of current longitudinal and lateral control technologies depends on the availability of accurate dynamic models of vehicles. However, it is well known that an universal dynamic model for automobiles is practically not feasible. Furthermore, due to the complex and time-varying nature of dynamic properties of an ordinary automobile, its control system must deal with a strongly nonlinear process in the presence of disturbances such as obstacles and ambiguous information coming from the sensors. It is well known that linear control theory lacks a proper paradigm for modeling such a complex system. This is especially true for the lateral control problem.

Therefore, innovative control methods that do not require an accurate model of vehicle dynamics and yet provide adequate or even optimal performance for different driving conditions must be investigated. Realizing that a person can drive a vehicle with great skill but without knowing anything about the vehicle's analytical dynamic model, the research team believes that the best scenario here is a control system that can mimic human driving behavior (but must have faster response to changes in driving conditions).

For this purpose, the research team will develop and test a **fuzzy-logic** based control design for both longitudinal and lateral controls. Over the last six years, the members of the research team have demonstrated successfully that rule-based fuzzy control methods, which can incorporate easily heuristics and human skills in control design, can be used to control complex systems without utilizing explicit models of system dynamics. For example, using fuzzy control, UA has developed a control system for a heavy-duty wheel loader to autonomously dig in difficult mining environments. This system has been built with fuzzy control rules that mimic actions taken by a skilled human operator in similar situations. The initial test results on Caterpillar

980G Wheel Loader have been very successful, showing performances better than other control technologies tested so far. The same techniques can be applied to automated vehicle driving. Actually, using fuzzy logic it may be easier to drive vehicles on well-defined lanes than to dig for material in unstructured dynamic mining environments, since there is an abundance of human driving skills and experience that can be utilized in this case.

4.3 Hierarchical Control System

Traditional control system designs for vehicle systems have been based on a framework of functional decomposition into sensing, planning and acting components. Such a framework normally demands a significant overhead in terms of computational effort, communication time, and decision-making capability. Within this framework, even a very simple task has to be processed through a full scale of operational activities.

A behavior-based method, however, takes a different approach by decomposing a control problem into special-purpose task-achieving programs. Usually, these programs are coupled directly to sensory information and can be constructed using simple computations with minimal memory needs, and may be implemented with inexpensive and simple hardware. Such an approach has been studied extensively and applied successfully for mobile robot control systems.

The research team's proposed vehicle control is based on a set of simple and specific task-achieving behavior programs for sensing and actuation using fuzzy logic. Each behavior program will be described by a set of fuzzy decision rules and fuzzy linguistic variables. In this way, the process of converting human skills and experience for different driving conditions into microprocessor-based control algorithms can be greatly facilitated. Examples of specific behavior programs include line-follower, frontal-collision avoider, distance-follower, etc. In order to achieve coherent *IVA* operation, these behavior programs must be integrated. To this end, system control architecture for automated vehicle driving will be constructed according to the hierarchical structure developed for intelligent machines [Wang and Saridis 1990] and robotic mining vehicles for lunar mining [Wang and Lever 1993], where behavior programs are arranged in two hierarchical levels: behavior coordination (for path planning), and behavior execution (for trajectory control). This hierarchical structure is well suited for integrating sensory information acquisition with task control functions required by intelligent vehicles.

4.4 Sensing Technologies

It is relatively easy to provide static position and preview information to an intelligent vehicle, for example through magnetic markers or through bar-codes that can be read via radar/laser. The *VISTA*'s Program goal is to use such inexpensive technologies to assist longitudinal and lateral control. The research team's strategy is to combine reliable sensing methods to provide long-range preview road information for open-loop path planning, with an inexpensive sensing method to obtain short-range current road information for real-time trajectory control. For example, we can use magnetic markers (or radar/laser readable bar-codes) to code road information on the next 100-300 meters (using curve fitting or other approaches). Using this information, an *IVA* will be able to identify its current position relative to the roadway for the next 100-300 meters, and plan its motion in advance for that distance/time horizon. Real-time vehicle position can be obtained using other sensing methods that cost less (but provide little preview information) such as ultrasonic sensors, lasers, FSS or other radar reference systems. This information will be used for real-time feedback control of the *IVA* trajectory.

It be noted that with the introduction of communication/electronic infrastructure on the intelligent lanes, the static information provided every, say, 100-300 meters may be updated to provide new dynamic information such as weather condition, scheduled road maintenance which will make the IV-AHS system even more robust and effective. This higher level dynamic control will be investigated at a later phase of the *VISTA* Program.

Figure 1 depicts the proposed sensing and hierarchical architecture for the IV-AHS system. It is anticipated that this strategy will have the following advantages:

(a) *It will be cost effective.*
Long-range more expensive sensing devices will be implemented at much larger intervals, thereby decreasing communication infrastructure cost.

(b) *It will robust and reliable.*
Long- and short-range sensing strategies are complementary to each other. On one hand, long-range road information can simplify short-range sensing data processing and make its result more robust and accurate against failures and noises. On the other hand, short-range position information can facilitate the process of finding the relative position of the vehicle with respect to the roadway for the next 100-300 meters. Furthermore, the reliability for short-range sensing may be improved since the system is not restricted to single sensing

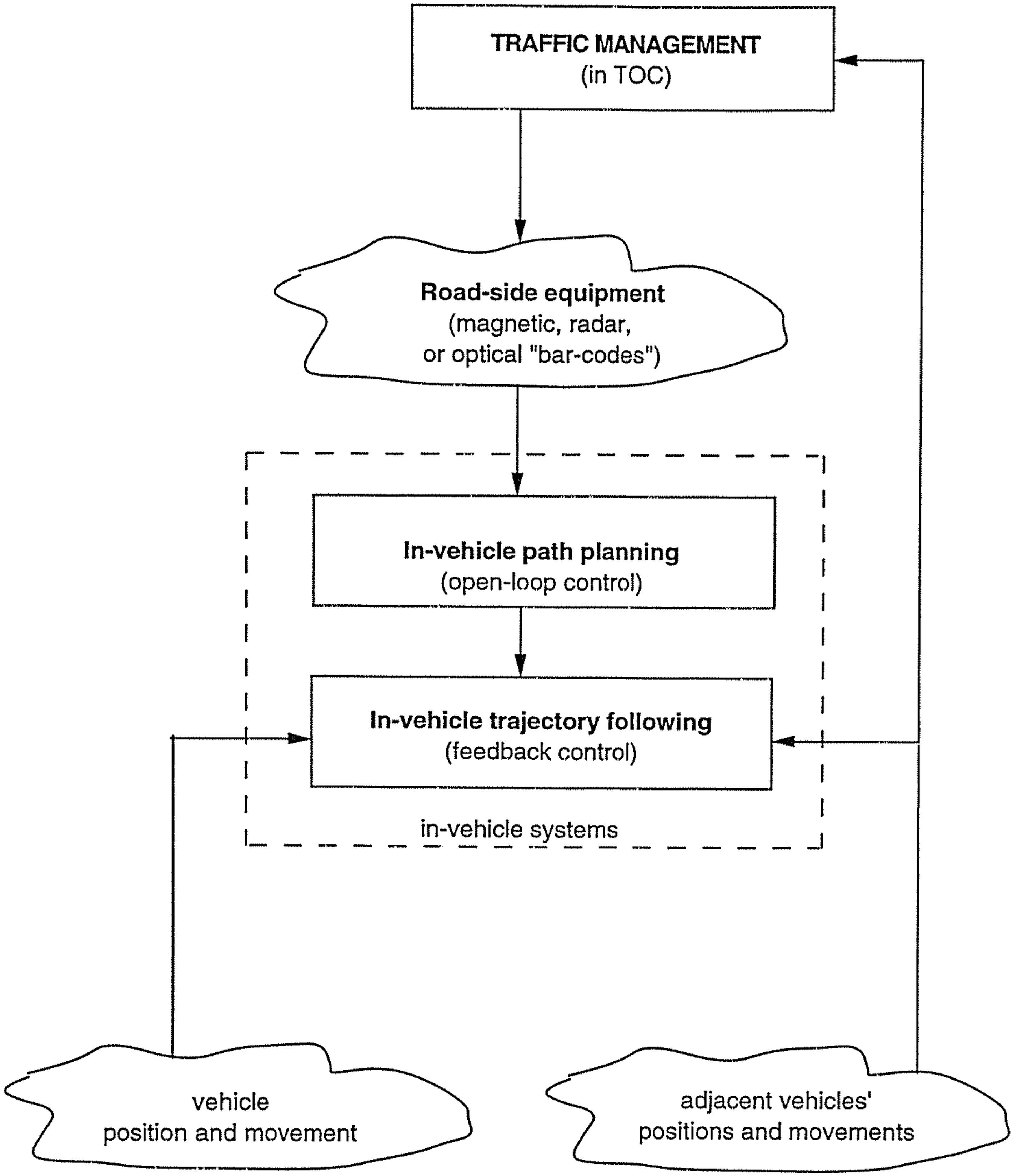

Figure 1: Hierarchical Control Architecture for Intelligent Vehicles

technology. Dead reckoning control algorithms using the long-range markers can safely assist the vehicle to appropriately respond when short-range sensors fail.

(c) *It will enable better control and motion.*
By providing both long- and short-range roadway information, path planning (open-loop control) and trajectory control (closed-loop feedback control) can be conducted in a hierarchical and optimized fashion. It should be pointed out that no current vehicle control system has the feature of path planning. This feature makes it possible for an IV to optimally schedule its speed and position for a longer time window, while the short-range road information provides the needed feedback to follow its lane closely at all times. Thus, optimal control algorithms for achieving smoother motion and minimum energy consumption can be implemented.

(Note that the concept of road markers has previously been proposed for IV-AHS. However, those markers provide only road information and offer no help in identifying the current position of a vehicle with respect to those markers. This makes them invalid for path planning. The proposed road markers and sensing strategy will do both, path planning and real-time feedback control.)

5. WORKSCOPE AND TASKS

The workscope for the proposed first year of the *VISTA* Program includes the following tasks:

Task 1: *Obtain and Enhance a Demonstration Vehicle*
Task 2: *Develop Longitudinal and Lateral Control Systems*
Task 3: *Develop Sensor Systems*
Task 4: *Demonstrate Intelligent Vehicle Concepts*
Task 5: *Compare and Evaluate Available IV Technologies*
Task 6: *Perform Preliminary Analysis of Tucson-Phoenix Intelligent Lanes*
Task 7: *Seek Partnerships for Research and Development Collaborations*
Task 8: *Prepare Final Report with Recommendations*

Task 1: Obtain and Enhance a Demonstration Vehicle

To emphasize the deployability of *VISTA*'s intelligent vehicle and automated highway system concepts, the demonstration vehicle will be a modification of an ordinary car that is widely used by commuters. Based on this consideration, the *VISTA* Team has tentatively decided to modify a passenger car that is to be leased by UA from ADOT's fleet. (If this is not possible, then the research team will buy a used vehicle.) The selection of the type of car from the fleet will be based on (1) the sufficiency of the size of engine chamber - so that enough open space is available to accommodate various actuators and systems required for the modification, (2) availability of interior space for both the control hardware equipment and 3 - 4 passengers, and (3) availability of cruise control. A study will be conducted before the research team makes the final decision on the make and model of the demonstration vehicle.

If a vehicle is to be leased from ADOT, a leasing agreement between UA and ADOT will be developed which will allow the research team to modify and use the vehicle during the research project, where the maintenance will be provided either through ADOT facilities (if they are convenient) or through UA/ASU facilities. Insurance and liabilities will be borne by UA.

Three major hardware modifications will be made on the selected vehicle. First, some electronic circuit design and rewiring will be performed so that the cruise control system can be operated by an on-board control computer. Second, a stepping servo motor will be coupled to the steering mechanism so that the control system can direct the vehicle's motion. Third, a translational actuator will be installed to control the braking action. The research team will visit the University of California (PATH Project) and CMU at the beginning of the project to investigate how these research groups have modified their intelligent vehicles.

Task 2: Develop Longitudinal and Lateral Control Systems

Based on the discussions in the previous section, the research team will use fuzzy control theory and the team's recent R&D results on fuzzy logic, to develop and evaluate, via simulation and field tests, fuzzy control programs for

i) long-range path planning;
ii) radar-based headway maintenance;
iii) radar-based road following; and
iv) close vehicle following (platooning).

Each of the above control programs will consist of a set of fuzzy rules which organize basic longitudinal and lateral vehicle commands. Many of these fuzzy control rules will be obtained directly from human driving behavior. Since fuzzy control rules use linguistic terms such as "if the distance between the two vehicle is little large, then increase the speed a little bit", human driving skills and experiences can be converted easily into fuzzy control programs. In the first phase of *VISTA* Program, a non-adaptive fuzzy technology will be used. Later, the research team will consider using the neuro-fuzzy method to add learning capability into the fuzzy control programs, for improving performance based on specific vehicle and road conditions.

Due to the simplicity of fuzzy control algorithms, the real-time on-board control system can be based on inexpensive hardware devises such as the Motorola VME162 CPU board or other similar units. The compiled controller code can be directly downloaded to such a device. This controller generates longitudinal and lateral control commands based on inputs from the sensors which provide information on the vehicle's motion and its position relative to other vehicles in the platoon and the roadway geometry/lanes.

Task 3: Develop Sensor Systems

In most of the intelligent vehicle systems described in the literature, each vehicle use devices such as optical encoders to measure its own speed and acceleration and uses ranging radar sensor to provide measurements of the relative speed and spacing between the preceding vehicle and itself. A vehicle may also receive acceleration information on the preceding vehicle via communications or through processing the measurements of the range sensor. Such information is sufficient for longitudinal control purpose.

For lateral control, some roadway reference system is needed. Several reference sensing systems have been proposed in the past. They include the permanent magnetic marker system, vision-based system and a side-looking radar system that uses a reference side wall. Ultrasonic as well as laser-based systems have also been proposed. The radar-based road reference systems track the vehicle's lateral position using, for example, the FSS technology. Although its installation is rather inexpensive, one disadvantage of the radar system is that it provides little preview information on the road. Therefore, its performance deteriorates with increasing speeds.

In this project, to take advantage of the best features of different reference systems and minimize the cost of the sensor system, a combination of radar (or possibly laser) and magnetic marker systems will be used. Radar (or laser) readable bar-codes, or bar-code-like magnetic marks, encoded with road curvature data will be installed significant distances apart (e.g., 100 to 300 meters apart with curve fitting data, which can describe these distances using three or four parameters) to provide preview information to the vehicle's control system. Different patterns of magnetic marks and/or bar-codes will be studied to find the best one for determining, effectively and reliably, the vehicle's position and orientation with respect to the designated lane. While the 100-300 meter encoded marks will provide the vehicle control system with road information for path planning, the intelligent vehicle will rely on a radar (or a laser-based) reference system between the marks to conduct maneuvers in real-time.

A detailed analysis of accuracy and reliability of such a sensing scheme will be conducted to determine the relationship between the inter-mark distances and the accuracy requirement for the vehicle control system.

Task 4: Demonstrate Intelligent Vehicle Concepts

Two types of demonstration experiments are planned in this project (in 1998-99) at least one of which will take place by December 1998. They are briefly outlined below.

(1) Lane Keeping Maneuvers of a Single Vehicle : The demonstration vehicle will be modified so that it is loaded with all the necessary equipment (such as sensors, actuators and control computers). In the test runs, *IVA* will be instructed to follow both straight and curved lanes of distances that are less than a mile. *IVA*'s performance will be evaluated, under constant and varying speeds, and under different weather conditions and disturbances such as missing road marks .

(2) Platooning : The major motivation of AHS platooning is the short inter-vehicle spacing that is insensitive to the vehicle speed and leads to higher capacity. Some researcher have claimed that platooning may increase the capacity of current highway systems by as much as 500%. To study AHS platooning, more than one IV is required. However, due to 1998-99 budget constraint for the project, only one intelligent vehicle is affordable. Therefore, to test platooning concepts, the IV will be instructed to follow a driver-operated vehicle at a fixed distance, along straight and curved lanes. (Nevertheless, the research team understands that more specially equipped vehicles may be added to this project if additional budget is released for that purpose.)

Task 5: Compare and Evaluate Available IV Technologies

Based on the studies, field tests, and demonstrations of the various technologies for sensor and control technologies for intelligent vehicles, the research team will make a comparison of the technologies and evaluate them for the purpose of developing designs for the Tucson-Phoenix Intelligent Lanes corridor. These evaluations and comparisons will be used for Task 6.

Task 6: Perform Preliminary Analysis of Tucson-Phoenix Intelligent Lanes

Based on the evaluations from Task 5, and the significant literature on available on cost and performance of various technologies, preliminary design alternatives for the Tucson-Phoenix Intelligent Lanes will be developed.

With the assistance of a facilitator, the research team will identify stakeholders (e.g., frequent I-10 commuters, truckers, bus operators, ADOT and city traffic engineers, Arizona Department of Public Safety (including Arizona Highway Patrol), state and local legislators, major industries effected by I-10 traffic, automobile insurance companies, automobile clubs, residents and landowners near I-10, etc.) who may be effected by the Tucson-Phoenix Intelligent Corridor and seek their input on the various design alternatives.

Task 7: Seek Partnerships for Research and Development Collaborations

Since the ultimate success and economic viability of intelligent vehicles and the automated highway systems depend on the benefits that they provide and the affordability of the general public to buy and use the corresponding intelligent vehicles, it is important that the entities that are most effected - frequent commuters, traffic agencies such as ADOT and USDOT - have "bought in" to research and development activities of *VISTA*. Hence, the research team will actively seek the collaboration, and possible funding, for future research through partnerships with other public agencies (in addition to ADOT and USDOT) and companies that may find *VISTA*'s research and products very beneficial. Because this task is very critical, *VISTA* will expend significant effort in seeking the above-mentioned partnerships.

Task 8: Prepare Final Report with Recommendations

Based on the findings of Tasks 1-7, a final report will be prepared providing details of the IV-AHS technologies/systems tested, their evaluations, viable alternative designs for IV lanes for the Phoenix-Tucson corridor, and recommendations for further research and design development.

6. MANAGEMENT PLAN AND INSTITUTIONAL QUALIFICATIONS

The three principal investigators of the project, Professors Mirchandani, Wang, and Kuo will provide the technical management of the project. Each of them bring to the project complementary expertise and strengths that will maximize the potential successes of the program. Most of the algorithmic and system development, including the bench test of software/hardware, will be conducted on the UA campus, where Professor Wang will coordinate the associated efforts of the faculty and students. The demonstration and the field testing will be conducted in the Tempe (at ASU) and in the Phoenix area, coordinated by Professor Kuo. Professor Mirchandani will coordinate the evaluation of system design alternatives for the Phoenix-Tucson corridor and will oversee the overall project performance, including facilitate UA-ASU interactions. All the three PI's will seek partners and colleagues for future collaborations and support since they have access to different funding organizations and R&D networks.

For the 1998-1999 academic year, the *VISTA* Program will be administered through the *ATLAS* Center, Systems and Industrial Engineering Department, The University of Arizona[2]. It will be overseen by the Engineering Experimental Station (EES) within the College of Engineering and Mines, and the Office of Sponsored Projects Services at the University-wide level. Most projects at the University of Arizona meet budget constraints and schedules -- unless the project sponsor specifically requires additional effort (for a cost) and/or provides extensions (with or without cost add-ons) to project completion date for mutually agreed-upon reasons.

Accounting will be done both at the *ATLAS* Center as well as at the university level (Office of Sponsored Projects Services) which prepares the invoices. The research team will provide quarterly progress reports to meet the quality/efficiency criteria of the project and as such preparation of the reports provide needed cost and quality control, for both the project manger and for the project sponsor.

The qualifications of the principal investigators and consultant Dave Bruggeman (BRW) are without reproach and are very relevant to the proposed Program. The attached Appendix gives their resumes. The institutional qualifications of The University of Arizona are also appropriate

[2] If the proposing team is awarded the project, the team will try and negotiate an institutional arrangement whereby both UA and ASU will be provided complementary contracts from ADOT with same negotiated overhead rate. Currently ATLAS and the College of Engineering and Mines at UA has a special negotiated overhead rate of 15%, while no such arrangements exist at ASU.

to conduct the proposed project. The Appendix also gives a brief summary of UA and its College of Engineering and Mines' qualifications.

Finally, note that, at the present, the research team is proposing a research program, entitled the *VISTA* Program, which will be administered through the *ATLAS* Research Center of Excellence being established at The University of Arizona. When the *VISTA* Program grows, as it is currently anticipated, Board of Regents approval will be sought for making this a multi-university research center.

7. BUDGET

Exhibit I gives the 1998-1999 budget for the *VISTA* Program. Most items are self-explanatory. The person-months efforts loaded for investigators Wang and Kuo are one month each, whereas Mirchandani is charged for half a month. The program will support two students, one at UA and the other at ASU, each at approximately 1/3 time over the calendar year.

The budget requests $16,000 for equipment. This is for leasing/buying a demonstration vehicle, a vision system such as RALPH (for $10,000) and for other equipment to modify the vehicle and install roadside sensors. The budget also requests funds for a subcontract with BRW for consultation with Mr. Dave Bruggeman (5 days).

Exhibit 1: 1998-1999 Budget for the *VISTA* Program

Budget for the *VISTA* Program Sept. 1, 1998 - Sept. 1, 1999	
Co-PI (F. Wang, UA)	$6,800
Co-PI (P. Mirchandani, UA)	$6,800
Co-PI (Kuo, ASU)	$6,800
Subtotal	$20,400
Graduate Assistant 2 students (ASU, UA)	$31,000
Admin. Assist./ Sec.	$2,249
Total Direct Labor	$53,649
ERE	
Investigators(18.5%)	$3,774
Students(3.1%)	$961
Staff(23.2%)	$522
Subtotal ERE	$5,257
Travel	$4,300
Operations	$2,500
Equipment (car, vision system, electronics)	$16,000
Consultant (Dave Bruggeman, BRW Inc.)	$5,250
Total Direct	$86,956
Indirect Costs (15%)	$13,044
Grand Total	$100,000

REFERENCES

Bayouth, M., and Thorpe, C. "An AHS Concept Based on an Autonomous Vehicle Architecture", *Proceedings of 3rd Annual World Congress on Intelligent Transportation Systems*, 1996.

Bruggeman, D. W., *Concept Study: Intelligent Express Lanes I-10, Phoenix to Tucson*, Technical Report to the Arizona Department of Transportation, December 1997.

Pomerleau, D. and Jochem, T. "Rapidly Adapting Machine Vision for Automated Vehicle Steering," *IEEE Expert 11*, 1996.

Ozguner, U. et al. "The OSU Demo '97 Vehicle" *Proceedings of IEEE Conference on Intelligent Transportation Systems*, Boston MA, November 1977.

Thorpe, C., and Jochem, T. *Automated Highways And The Free Agent Demonstration*, CMU Technical Report, 1998.

Varaiya, P. "Smart Cars on Smart Roads: Problems of Control", *IEEE Trans. on Automatic Control 38*, pp. 195-207, 1993.

Wang, F-Y., and Saridis, G.N., "A Coordination Theory for Intelligent Machines," *IFAC Journal Automatica, 26,* pp. 833-844, 1990.

Wang, F-Y., and Lever, P.J.A., "An Intelligent Robotic Vehicle for Lunar and Martian Resource Assessment," *Recent Trends in Mobile Robots* (edited by Y.F. Zhang), World Scientific Series in Robotics and Automated System 11, 1993.

Zhang, W-B., "National Automated Highway System Demonstration: A Platoon System" *Proceedings of IEEE Conference on Intelligent Transportation Systems*, Boston MA, November 1997.

APPENDIX

QUALIFICATIONS

PITU B. MIRCHANDANI

EDUCATION

Sc.D., Operations Research, Massachusetts Institute of Technology, January 1975.
M.S., Aeronautics and Astronautics (Man-Machine Systems), MIT, June 1971.
M.S., Engineering (Control Systems), UCLA, December 1967. University Fellow.
B.S., (Highest Honors), Engineering, UCLA, September 1966.

ACADEMIC AND PROFESSIONAL EXPERIENCE (last 10 years)

1990-Present: University of Arizona, Tucson, Arizona
Professor and Head, Systems and Industrial Engineering

1989: (Fall Sabbatical from RPI)
Massachusetts Institute of Technology
Visiting Professor, Operations Research Center

Boston University
Visiting Professor, Manufacturing Engineering Department

1987-1990: Rensselaer Polytechnic Institute, Troy, New York
Professor, Electrical, Computer and Systems Engineering
Professor, Decision Sciences and Engineering Systems

1984-1987: Rensselaer Polytechnic Institute, Troy, New York
Chairman, Operations Research and Statistics Program

PUBLICATIONS (Recent relevant publications from a list of over 60)

"Routes and Flows in Stochastic Networks" (jointly with H. Soroush), **Advanced School on Stochastics in Combinatorial Optimization**, (edited by G. Andreatta, F. Mason, P. Serafini), World Scientific Pub. Co., 1987.

"Concurrent Routing, Sequencing, and Setups for a Two-Machine Flexible Manufacturing Cell," **IEEE Journal of Robotics and Automation, 4**, (with E.J. Lee), 1988, pp. 256-264.

"Stochastic Dispatching of Multi-priority Jobs to Heterogeneous Processors" (with S. H. Xu, S. P. Kumar and R. R. Weber), **Journal of Applied Probability, 28**, pp. 852-861, 1990.

"Routing, Scheduling, and Risk Analysis for Hazardous Materials Transportation: The State of the Art" (with G. F. List, M. A. Turnquist, and K. G. Zografos), **Transportation Science, 25**, pp. 100-114, 1991.

"A Hierarchical Framework for Real-Time Traffic Control," (with K. L. Head and D. Sheppard), **Transportation Research Record 1360**, pp 82- 88, 1992.

"REALBAND: An Approach for Real-Time Traffic Coordination of Traffic Flows on Networks," (with Paolo Dell'Olmo), **Transportation Research Record, 1494**, pp. 106-116, 1995.

"A Model for Real-Time Traffic Coordination Using Simulation Based Optimization," (with Paolo Dell'Olmo), **Advanced Methods in Transportation Analysis**, (eds. L. Bianco and P. Toth), Springer-Verlag, 1996.

"A Simulation-Based Methodology for the Evaluation of High Occupancy Vehicle Facilities. (with D. Sheppard, K.L. Head and S. Joshua), Transportation Research Record 1554, pp 90-98, 1996.

"Experiments Comparing Deterministic and Stochastic Loading Models", (with M. Tatineni, and D. Boyce), Transportation Research Record, 1607, pp. 16-23, 1997.

"Prediction of Network loads based on Origin-destination Synthesis from Observed Link Volumes," (with Y. Ding and S. Nobe), Transportation Research Record, 1607, pp. 95-104, 1997.

RESEARCH GRANTS AND CONTRACTS (last 5 years)

Principal Investigator: "ATMS Support Systems" subcontract from Loral AeroSys (prime contractor) for USDOT Federal Highway Administration Contract DTFH61-92-R-00073 to consortium including TASC and KLD & Associates, October 1992 - September 1997, (with co-principal investigator K.L. Head). ~ $274K

Principal Investigator: "RHODES - Integrated Traffic Management System", Arizona Department of Transportation, Dec 1993 - date. (with co-principal investigator K.L. Head) ~$550K

Principal Investigator: "Development of a prototype Real-Time Traffic Adaptive Signal Control Strategy" from USDOT Federal Highway Administration Contract DTFH61-94-R-00010 June 1994 - September 1995, (with assistant principal investigator K.L. Head). ~ $400K

Co-principal Investigator: "Development of a Living Transportation Technology Laboratory" from the City of Tucson, May 1995 - date. (with co-principal investigator L. Head). ~ $200K for 2 years (anticipated total award $500K for 5 years)

Principal Investigator: "An Open Systems Communication/Control Architecture for Real-Time Traffic Adaptive Signal Control" from USDOT Federal Highway Administration Contract September 1997 - date, (with co-principal investigator K.L. Head, and teaming with Gardner-Rowe Systems, Inc. and Kaman Sciences, Inc.) ~ $400K

Other Academic and Professional Activities

- Professional Societies: IEEE, TIMS, ORSA, RSA, IIE, ACM, MPS, TRB, ITS America
- Past Associate Editor, **Transportation Science.**; on Editorial Boards of **J. Advanced Transportation, Mathematics of Industrial Systems and IIE Transactions**
- Program Chair for the Phoenix ORSA/TIMS Meeting, Nov. 1993.
- Organized workshop on "Real-Time Control Systems: Future and Implementation Barriers", supported by ADOT/PAG. Outside experts and some faculty from UA were invited, June 1991.
- Established research/education collaboration (partially funded by a UA International Programs Grant) with Dr. Nicolo of the University of Rome and Dr. Bianco of the Italian National Research Institute, on Automation and Traffic Control. Spent one month with them as a Visiting Professor. Two visiting scientists have come to the department for 6-month periods (A. Agnetis, U. Rome -1991, P. Dell'Olmo, CNR -1992)
- Organized and developed the Arizona Traffic Engineering Community (AZTEC) group, consisting of traffic engineers from ADOT, Arizona Transportation agencies, ASU and UA, April 1992.
- Recipient David Rist Best Paper Prize given by the Military Operations Research Society, (co-authors Michael McGinnis and Emmanuel Fernandez), May 1995.
- Have been consultant for several public and private sector organizations in the areas of location, scheduling and logistics, manufacturing, transportation, and education.

FEI-YUE WANG

The University of Arizona

Educational Background

BS *Chemical Engineering*, Shandong Institute of Chemical Technology, Qingdao, China, Nov. 1982. *Senior Project*: Design of 4M8-Reciprocating Compressor.
MS *Mechanics*, Zhejiang University, Hangzhou, China, Nov. 1984. *Thesis*: A Refined Theory for the Bending of Thick Orthotropic Shells.
PhD *Computer and Systems Engineering*, Rensselaer Polytechnic Institute, Troy, New York, Aug. 1990. *Thesis*: A Coordination Theory for Intelligent Machines.

Professional Employment History

1996-Present: *Associate Professor*,
1991-1996: *Assistant Professor*, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona 85721.
1987-90: *Research and Teaching Assistant*, NASA Center for Intelligent Robotic Systems for Space Exploration and Center for Manufacturing Productivity and Technology Transfer, Rensselaer Polytechnic Institute, Troy, New York 12180.
1984-86: *Instructor*, Mechanics Department, Zhejiang University, Hangzhou, China.

Honors and Awards

Caterpillar Research and Invention Award, Caterpillar Inc., Peoria, IL, 1996. (shared the $30,000 with Dr. P.J.A. Lever).
Nomination for 1995 and 1996 NSF Presidential Faculty Fellow Award by the University of Arizona as the only faculty member in engineering.

Memberships

Senior Member, The Institute of Electrical and Electronics Engineers (IEEE).
Member: Sigma Xi, 1990; National Council on Systems Engineering (NCoSE); Association for Computing Machinery (ACM).

Service to Professional Communities

Editor-in-Chief, International Journal of Intelligent Control and Systems.
Editor-in-Chief, Series on Intelligent Control and Intelligent Automation.
Specialist Referee, University and Polytechnic Grants Committee, Hong Kong.
Program Chair, IEEE Int'l Symp. on Intelligent Control, Gaithersberg, MD. 1998.
Chairman, IEEE Working Group on Manufacturing Systems Design.

List of Selected Relevant Publications

1. Fei-Yue Wang, P. Lever, and X. B. Shi. Fuzzy Behavior Fusion and Integration for Robotic Excavation. *IEEE Trans. on Industrial Electronics*. June. 1996.

2. X. B. Shi, Fei-Yue Wang and P. Lever, Experimental Results of Robotic Excavation using Fuzzy Behavior Control, submitted to *IFAC J. Control Engineering Practice*, Feb., 1996.

3. Fei-Yue Wang and G.N. Saridis, Task Translation and Integration Specification in Intelligent Machines, *IEEE Trans. on Robotics and Automation*, RA-9 (3), 1993.

4. Fei-Yue Wang, P. Lever, and D. Chen, Rule Generation and Modification for Intelligent Controls using Fuzzy Logic and Neural Networks, *J. of Intelligent Automation and Soft Computing*, Vol. 4(2), 1997.

5. Fei-Yue Wang and H.M. Kim, Implementing Adaptive Fuzzy Logic Controllers with Neural Networks: A Design Paradigm, *J. of Intelligent and Fuzzy Syst.*, Vol.1 (3), 1995.

6. Fei-Yue Wang, Building Knowledge Structure in Neural Networks using Fuzzy Logic, in *Robotics & Manufacturing: Recent Trends*, Ed. M. Jamshidi, ASME Press, 1992.

7. Fei-Yue Wang and P. Lever, A Cell Mapping Method for General Optimum Trajectory Planning of Multiple Robotic Arms, *J. of Robotic and Autonomous Syst.*, Vol.12, 1994.

8. P. Lever, Fei-Yue Wang, and X. Shi, Autonomous Robotic Mining Excavation using Fuzzy Logic and Neural Networks, *J. of Intelligent and Fuzzy Systems*, Vol.1 (4), 1994.

Related Research Projects

1. Co-PI (25% effort), *High-Autonomous Control System for Lunar/Martian Oxygen Production Plant*, $220,000, UA/NASA Space Engineering Research Center, 1991-93.

2. PI (100% effort), *An Intelligent Vehicle System for Lunar/Martian Applications*, $28,000, UA/NASA Space Engineering Research Center, 1992-93.

3. Co-PI (50% effort), *A Vision-Based Intelligent Real-Time Control System for Mining Tasks in Dynamic Environments*, $11,774, MMRRI of Dept of Energy, 1992-93.

4. PI (50% effort), *Automated Robotic Mining Excavation using Fuzzy Logic and Neural Networks*, $36,600, National Science Foundation, 1994-95.

5. Co-PI (50% effort), *Development of a Computer-Based Scheduling Model for Planning and Operational Control of Leach Operations*, $43,344, Copper Range Co., MI. 1995-96.

6. Co-PI (50% effort), *Development of Robotic Excavation Technology*. $1,045,837. Caterpillar. Peoria. IL, 1996-1998.

7. PI (50% effort), *Computer Direct Distributed Control for BGA Process*. $20,000. Vanguard Automation. Inc., Tucson. 1997.

C. Y. KUO

Department of Mechanical and Aerospace Engineering
Arizona State University
Tempe, AZ 85287-6106

Degrees:

Ph.D.	University of California, Berkeley, 1985
M.S.	Northwestern University, 1980
B.S.	National Taiwan University, Taipei, 1979

Academic Experience:

1992-present	Associate Professor, Mechanical and Aerospace Engineering Department, Arizona State University.
1986-1992	Assistant Professor, Mechanical and Aerospace Engineering Department, Arizona State University.
1980-198	Research Assistant, Mechanical Engineering Department, University of California, Berkeley.

Principal Areas of Research Interest:

Intelligent Control of Mechanical Systems, Control of Unstable Systems, Neural Network Systems, Robot Control, Active Control of Flexible Structure Vibrations, Missile Guidance, Robust Control, Microcomputer-Based Control System Design, Instrumentation.

Selected Journal Publications:

Kuo, C. Y., Louie, J. K. and Mote Jr., C.D., "Field Measurements in Snow Skiing Injury Research," *J. of Biomechanics, 16(8)*, 609-624, 1983.

Louie, J. K., Kuo, C. Y., Gutierrez, M. D. and Mote Jr., C.D., "Surface EMG Measurements and Torsion during Snow Skiing: Laboratory and Field Tests," *J. of Biomechanics, 17(10)*, 713-724, 1984.

Kuo, C. Y. and Worger, W. "Application of Model Reference Adaptive Control to PUMA 560 Robotic Manipulator," *ASME Trans., Journal of Dynamic Systems, Measurement and Control, 109(3)*, 294-297, 1987.

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BRW

Dave Bruggeman, PE
Vice President
Regional Director of Traffic Engineering/ITS Deployment

Education

Bachelor of Science in Civil Engineering, University of Arizona (1979)
Undergraduate in Electrical Engineering, Purdue University (1972-1975)
FHWA Training:
- Management of Traffic Control Systems
- Traffic Control Devices

Traffic Signal Systems Training:
- Safetran Type 170 Control System/332 Cabinet
- BiTrans 200SA/210 Quicnet System Control and Maintenance
- Wapiti W4IKS

Institute of Transportation Engineers Training:
- Traffic Access and Impact Studies for Site Development

American Association of State Highway and Transportation Officials:
- Roadside Barriers Design

Econolite & Cohu:
- Traffic Management Systems Design

American Traffic Services Association Training:
- Worksite Traffic Control Design

Professional Affiliations

Registered Professional Engineer: Arizona, Texas, New Mexico, Nevada, Montana, Washington, California (Traffic), Oregon, Colorado, Utah, Missouri (Pending, 7/98)
Institute of Transportation Engineers, Fellow
Institute of Transportation Engineers, ITS Council, Charter Member
Institute of Transportation Engineers, Chairman, Technical Committee 4D-3, "Signing and Striping Guidelines for Off-Street Developments"
Transportation Research Board, Associate Member
National Committee on Uniform Traffic Control Devices, Traffic Signal Standards Committee, Voting Member
National Committee on Uniform Traffic Control Devices, Traffic Signal Standards Committee, Visibility Cone of Vision Task Force
ITS America, Charter Corporate Member
ITS Arizona, Charter Member
ITS Arizona, Board of Directors, Past President
ITS Arizona, Board of Directors, Past Treasurer
ITS Arizona, Board of Directors, Director
National Transportation Communications and ITS Protocol Lite (NTCIP Lite) Committee, Member
National Advanced Traffic Controllers (ATC) Committee, Associate Member
National NTCIP Protocol Committee, Associate Member

Experience

BRW, Inc. (1989 to Present). Mr. Bruggeman is Vice President of the firm, serving as head of BRW's Traffic Engineering/ITS Deployment division for the Western Region.

City of San Antonio, Texas (1986 - 1989). Mr. Bruggeman was responsible for all aspects related to traffic signal timing, design, maintenance and operations, consultant selection, contract administration and standards development for the nation's 9th largest City, with over 1,100 traffic signals. Mr. Bruggeman was Project Manager for the development and implementation of BiTran 200SA (SA=San Antonio) software for the Type 170 controllers.

City of Tucson, Arizona (1978 - 1986). Traffic Project Engineer for traffic studies, traffic signal construction, traffic operations, development of standards, consultant selection, signing, striping, and administration of design contracts. Mr. Bruggeman designed, administered and field inspected the construction of over 100 traffic signals, including the design of decorative signal support structures.

ITS Projects

- Roadway Deployment Analysis Task Manager for the FHWA's Automated Highway System Precursor System Analysis;
- I-10 Automated Expressway Lanes Study, including demonstration of two different automated vehicle technologies and presentation to State Legislature;
- Roadway Operations Analysis Task Manager for the FHWA's Automated Highway System Precursor System Analysis;
- Technical expert in charge of review and comment for the development of the Automated Highway System concept developed by the Battelle Foundation;
- Technical expert in charge of review and comment for the development of the Automated Highway System concept developed by Honeywell;
- Traffic Engineer for the Gary-Chicago-Milwaukee ITS Priority Corridor ITS Plan;
- Red Light Enforcement Camera System Infrastructure and field elements, Lincoln & Tatum, Paradise Valley, AZ;
- Task Leader for Technology Evaluation for the City of Lancaster Bus Priority System Feasibility Study for Lancaster, CA;
- FMS infrastructure design for support of fiber optic backbone, ramp metering, VMS, and CCTV along the SR 101 Price Freeway, Warner Road to Frye Road;
- FMS infrastructure design for support of fiber optic backbone, ramp metering, VMS, and CCTV along the SR 51 Squaw Peak Freeway, Shea Road to Thunderbird Road;
- Revisions to the FMS Phase IV PS&E to accommodate relocation of CCTV sites and modifications to fiber optic backbone;
- Phoenix area ramp metering project, deploying ramp metering and modification of existing ramp metering systems at 24 locations in the Phoenix metropolitan area;
- Design of 5 variable message sign (VMS) sites along I-40;
- Design of 9 remote weather information systems (RWIS) in northern Arizona;
- Design of modifications to 3 mountaintop communications sites for the Department of Public Services (DPS) in northern Arizona;
- Design of 4 VMS sites in the Kingman, Arizona District;
- Concept Definition Study of the regional traffic management center (TMC) for the Phoenix metropolitan area for Maricopa County DOT;
- Specifications for the equipment and system integration tasks for the Maricopa County Phoenix regional TMC in Phoenix, AZ.;

Traffic Signal Systems & Communications

- Feasibility Study, design, and implementation of the downtown Closed Loop traffic signal system for the City of Davenport, Iowa, utilizing Eagle EPAC controllers and hardwire interconnect

- City of Kansas City, Kansas, Traffic Signal and Communications System Feasibility Study;
- Development of the conceptual design and equipment specifications for the Maricopa County Regional Traffic Management Center in Phoenix, AZ;
- City of Gilbert Traffic Signal and Communications System Feasibility Study;
- Design of controllers, cabinets, communications, and WWV elements for a City-wide conversion from NEMA to Type 170 controllers for the Town of Paradise Valley, AZ, utilizing BiTran 200SA local software;
- Design of the controller and communications elements for the City of Phoenix distributed intelligence ATMS traffic signal system, utilizing fiber optics and telephone drops coupled to Econolite TS 2 controllers and a hybrid distributed system;
- City of Phoenix Traffic Signal and Communications System Feasibility Study;
- Design, timing development and implementation of the Town of Prescott Valley Traffic Signal System, utilizing Type 170 controllers operating with BiTran software with WWV and a Spread Spectrum interconnect system;
- Design, timing development and implementation of the City of Goodyear signal timing, utilizing Eagle EPAC controllers;
- Design, timing development and implementation of the City of Prescott signal timing, utilizing Econolite TS2 controllers;
- Design, timing development and implementation of the City of Los Alamos, New Mexico, signal timing, utilizing TCT LMD8800 controllers;
- City of Chandler Signal System and Manpower Needs Evaluation for the traffic signal system upgrade to a Monarc system, utilizing Eagle EPAC controllers;
- Design of the Closed Loop traffic signal system for Greenwood Village, Colorado, utilizing fiber optics communications and Type 170 controllers operating with Wapiti software;
- Design of the City of Flagstaff, Arizona downtown Closed Loop traffic signal system, utilizing Eagle EPAC controllers and a City-owned cable interconnect system;
- Implementation assistance for the Riverdale Traffic Signal System in Anoka County, Minnesota, utilizing NEMA TS 1 controllers;

Signal Timing

- Design and implementation of coordinated arterial signal timings for Elliot, Warner, Alma School and Dobson Roads in Chandler, Arizona, utilizing Eagle EPAC controllers;
- Development and implementation of signal timing for a work zone flagman traffic signal in Beaver Creek, Oregon, utilizing Type 170 controllers with Wapiti software. Project included setup and activation of Peek video detection;
- Development and implementation of coordinated arterial signal timings for Paradise Boulevard in Los Alamos, New Mexico, utilizing TCT NEMA TS 1 controllers. Project included review of Peek video detection to insure proper setup and detection zone definitions;
- Design and implementation of coordinated arterial signal timings for Gurley Street, in Prescott, Arizona, utilizing Econolite TS 2 controllers;

- Design, implementation and staff training for traffic signal timings for ADOT on US 95 in Bullhead City, Arizona, utilizing Econolite TS 1 controllers. This project included training of ADOT staff in the development, installation and tuning of coordinated signal timings;
- Design of interconnect, development and implementation of coordinated arterial signal timings for all of the traffic signals in Prescott Valley, Arizona, utilizing Type 170 controllers with BiTran software;
- Design of interconnect, development and implementation of coordinated arterial signal timings for all of the traffic signals in Paradise Valley, Arizona, utilizing Type 170 controllers with Wapiti W4IKS software. This project included training of City staff in the development, installation and tuning of coordinated signal timings;
- Design of interconnect, development and implementation of coordinated arterial signal timings for 30th Street and Sweetwater Drives in National City, California, utilizing Type 170 controllers with BiTran software. This project included training of City staff in the development, installation and tuning of coordinated signal timings;
- Evaluation and design of new signal timings for all signals along six major arterials in Chandler, Arizona, utilizing Eagle EPAC controllers;
- Design of interconnect, development and implementation of coordinated arterial signal timings for Plaza Boulevard in National City, California, utilizing Type 170 controllers with BiTran software. This project included training of City staff in the development installation and tuning of coordinated signal timings;
- Design and implementation of coordinated arterial signal timings for Litchfield Road in Goodyear, Arizona, utilizing Eagle EPAC controllers;
- Development and implementation of coordinated arterial signal timings for National City Boulevard in National City, California, utilizing Type 170 controllers with BiTran software;
- Development and implementation of coordinated arterial signal timings for the downtown area in El Cajon, California, utilizing Type 170 controllers with BiTran software;
- Development and implementation of signal timings for the on-site traffic signals for Universal Studios, in Los Angeles, California, utilizing Type 170 controllers with BiTran software;

Traffic Signal Operations

- Traffic signal efficiency study for the Las Vegas Resort Corridor;
- I 10/SR 287 Operations Study, Casa Grande, AZ;
- Speed Limit Study, Goodyear, AZ;
- Kiva & Cherokee Schools Traffic Circulation & Safety Study, Paradise Valley, AZ;
- Traffic engineering analysis for the Downtown Traffic Circulation Study for City of Tucson, Arizona;
- Traffic engineering analysis for the Downtown Traffic Circulation Study for the City of Las Vegas, Nevada;
- Signal Preemption Technologies Study and Demonstration, City of Scottsdale, Arizona;
- Signal Preemption Technologies Study and Demonstration, City of Phoenix, Arizona;

Reversible Lane Systems

- Design of electronic reversible lane operation using fiber optic signs and coordinated controls in Denver, Colorado;
- Feasibility study and conceptual design of reversible lane facilities in Salt Lake City for the Utah Department of Transportation;
- Leetsdale Drive Reversible Lane Feasibility Study and Conceptual Design in Denver, Colorado;

Transportation Planning

- Chandler Downtown Plan Traffic Circulation Study, Chandler, AZ;
- Intel Chandler Campus Safety Study, Chandler, AZ;
- Intel Ocotillo Campus Safety Study, Chandler, AZ;
- Chaparral Corridor Study, Scottsdale, AZ;
- Verde Valley Transportation Plan, Verde Valley, AZ;
- Winslow Transportation Plan, Winslow, AZ;
- Southern Apache County Transportation Plan, AZ;
- Camp Verde Transportation Plan, Camp Verde, AZ;
- Sedona Circulation Element of General Plan, Sedona, AZ;
- Fountain Hills Circulation Element of General Plan, Fountain Hills, AZ;
- SR 280 Corridor Study, Yuma, AZ;
- Williams Air Force Base Campus Master Plan;

Litigation

- Biltmore Fashion Square, Phoenix, AZ;
- Sands Hotel & Casino, Las Vegas, NV;

Traffic Impact Studies

- Phoenix Indian School Downtown Site, Phoenix, AZ;
- Basha's Fiesta, Chandler, AZ;
- Chandler Mosque, Chandler, AZ;
- Microchip Technology Plant Expansion, Chandler, AZ;
- Prescott Signal Warrants Studies, Prescott, AZ;
- Willow Creek Rd. Warrants Studies, Prescott, AZ;
- Signal Warrant Studies, Prescott Valley, AZ;
- 701/801 Downtown Parking Structure, Phoenix, AZ;
- Shopping Center at 59th Avenue/Beardsley Rd., Glendale, AZ
- Phoenix Indian School Central Ave. Site, Phoenix, AZ;
- Papago Unit 3 Circulation Study, Phoenix, AZ;
- Boswell Hospital Circulation Study, Sun City, AZ;
- Sands Convention Center Circulation Study, Las Vegas, NV;
- Smith's Center, Globe, AZ;

The University of Arizona: Qualifications and Experience

The University of Arizona is a leading research institution, earning national recognition for programs in such fields as electronics, optical sciences, medicine, scientific instrumentation, astronomy, geology, and systems engineering. The University has a Research I classification, is a member of the prestigious Association of American Universities, and is consistently ranked among the top twenty research universities in the United States. Recently, the University of Arizona ranked 17th among all American universities and 11th among public institutions. Research expenditures total over $200 million annually.

The University of Arizona enrolls more than 35,000 students, about a quarter of whom are pursuing graduate studies. The University offers bachelors degrees in 142 fields, masters degrees in 140 fields, doctoral degrees in 97 fields, specialist degrees in 9 fields, and 3 professional degrees. For the 1990-91 academic year, the University enrolled more than 150 national merit scholars. It has also enrolled 88 of the first 100 Flinn Foundation scholarship students. The Flinn scholarship program is a highly competitive program for the top seniors in Arizona high schools.

Academically the University of Arizona consists of eleven colleges:

- Agriculture
- Architecture
- Arts & Sciences
- Business & Public Administration
- Education
- Engineering & Mines
- Graduate College
- Law
- Medicine
- Nursing
- Pharmacy

as well as eight schools and a few of other special academic units. Each year all the University produces about 5,000 graduates, a third of whom earn graduate degrees.

About 2,000 (FTE) of the University of Arizona's more than 10,000 (FTE) employees are members of the instructional and research faculty. Many of these faculty members have distinguished themselves through their teaching and research. Among the special honors and awards they have received are a Nobel prize; Pulitzer prizes in fiction, poetry, and journalism; Sloan fellowships; Guggenheim fellowships; Fullbright awards to work abroad in numerous fields; and over a dozen memberships in the prestigious National Academies of Science and Engineering.

The College of Engineering & Mines

The College of Engineering & Mines has its origins in the land grant mission of the University of Arizona and continues to be a principal bearer of these commitments and values.

Currently, the College includes ten academic units, spanning a broad range of engineering programs.

- Agricultural & Biosystems Engineering
- Aerospace & Mechanical Engineering
- Chemical Engineering
- Civil Engineering & Engineering Mechanics
- Electrical & Computer Engineering
- Hydrology & Water Resources
- Materials Science & Engineering
- Mining & Geological Engineering
- Nuclear & Energy Engineering
- Systems & Industrial Engineering

These departments are responsible for 49 degree programs, including 17 baccalaureate, 17 masters, and 15 doctoral programs.

The total faculty of the College includes nearly 200 persons. The strength of this faculty is in the combination and blending of strong senior faculty (including three members of the National Academy of Engineering) with an impressive group of young faculty (including six current holders of Presidential Young Investigator awards). Currently the level of research expenditures in the College is running at $13.5 million annually.

The faculty is strong, and so too are the students, particularly at the graduate level. The College has twelve National Merit Scholars and three Flinn Scholars. At the graduate level, students have won nationally competitive awards including IBM fellowships, Defense Department research fellowships, as well as prizes and other honors within their professional organizations. Current enrollments in the College include more than 3,000 undergraduate students and nearly 900 graduate students. The College has more than 18,000 alumni and alumnae.

Students and faculty from the College's departments participate in several multidisciplinary research programs. These programs are established (or are being established) within the following multidisciplinary centers and programs:

- Environmentally Benign Semiconductor Manufacturing Center
- Center for Electronic Packaging Research
- Biomedical Engineering
- Center for Separation Science
- Center for Material Modeling & Computational Mechanics
- Center for Microcontamination Control
- Advanced Traffic and Logistics Algorithms and Software Center
- NASA Earth Observing System
- Center for the Recovery & Utilization of Copper
- Laboratory for Advanced Subsurface Imaging
- Program for Advanced Integration of Manufacturing Systems & Technologies
- Center for Research in Emerging Technologies in Transportation Engineering

Relevant to this proposal, the College of Engineering and Mines has had considerable experience on funded projects from the Arizona Department of Transportation, mainly through the Systems and Industrial Engineering Department which houses the Center forAdvanced Traffic and Logistics Algorithms and Software (*ATLAS*) and the Center for Research in Emerging Technologies in Transportation Engineering (CRET^{2}E). In particular, ADOT has provided significant support on the development of the *RHODES* Traffic Adaptive Signal Control System which has received wide recognition, nationally as well as internationally.

ARIZONA DEPARTMENT OF TRANSPORTATION

Joint Project Administration

Progress	Final	Payment Report

Report No.	FA	Non FA	Exp. Budget Obj. Code	Contract No. JPA 98-156

TRACS No.
Project No. Date Ending

Name of Project:

Name Of Consultant:

Date Started	Estimated Completion Date:		% Billed	% Complete

SUMMARY OF WORK FOR WHICH PAYMENT IS REQUESTED

Item	Description	Total Contract Amount	Previous Accumulative Amount	Current Month	Accumulative Amount
1	Per JPA 98-156	$1,000,000.00			

Submitted By: ______________________ Date__________
University of Arizona

Approved By: ______________________ Date__________
ADOT Project Monitor

Approved By: ______________________ Date__________
Joint Project Administration

Total To Date		
Total Previous Report		
Current Report		